3M Science. Applied to Life.™

Advanced High Energy Li-ion Cell for PHEV and EV Applications

Jagat Singh, 3M

3M-EMSD. June 7th 2016

Project ID - ES210

"This presentation does not contain any proprietary, confidential, or otherwise restricted information"

Overview

Timeline

- Start Date:10/01/2013
- End Date:03/31/2016
- Percent Complete:100%

Barriers

- Cycle Life,
- Specific Energy,
- Cost

Budget

- Total Project Funding
  - $3,145,571
- DOE* Share
  - $2,250,043
- Contractor Share
  - $895,528

*3M and the team appreciates the support and funding provided by DOE

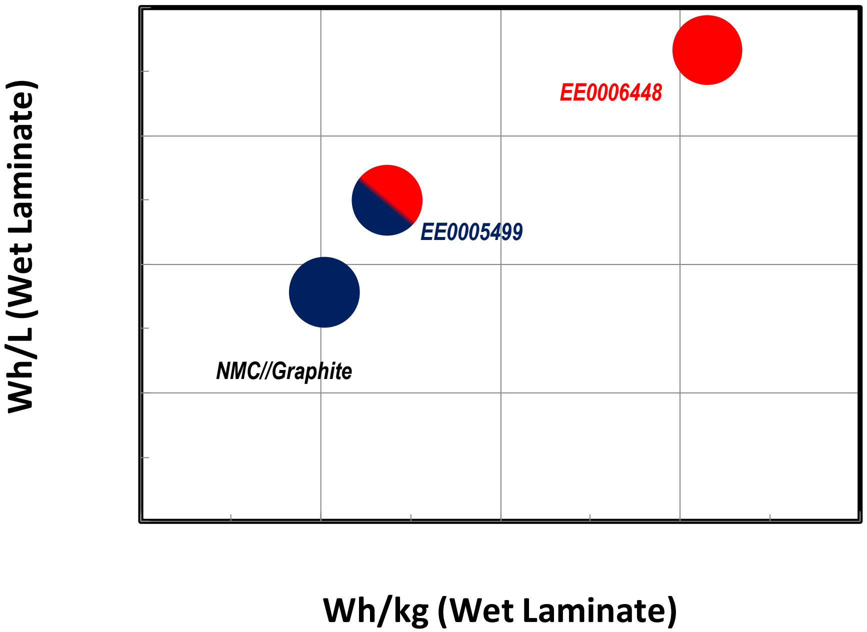
Partners

- Collaboration:
  - GM: Dr. Meng Jiang
  - Umicore: Wendy Zhou
  - Iontensity: Marc Juzkow
  - ARL: Dr. Richard Jow
  - LBNL: Dr. Gao Liu
- Interaction
  - Dalhousie University
  - ANL: Deliverable Testing
- Project Lead:3M

Relevance

A collaborative team approach to leverage crucial Li-ion battery technologies and expertise to help enable

- Advanced High Energy Li-Ion Cell
- Superior Performance Envelope
  - Long Cycle Life,
  - High Power Capability,
  - Wide Operating Temperature
- Lower Cost ($/Wh)

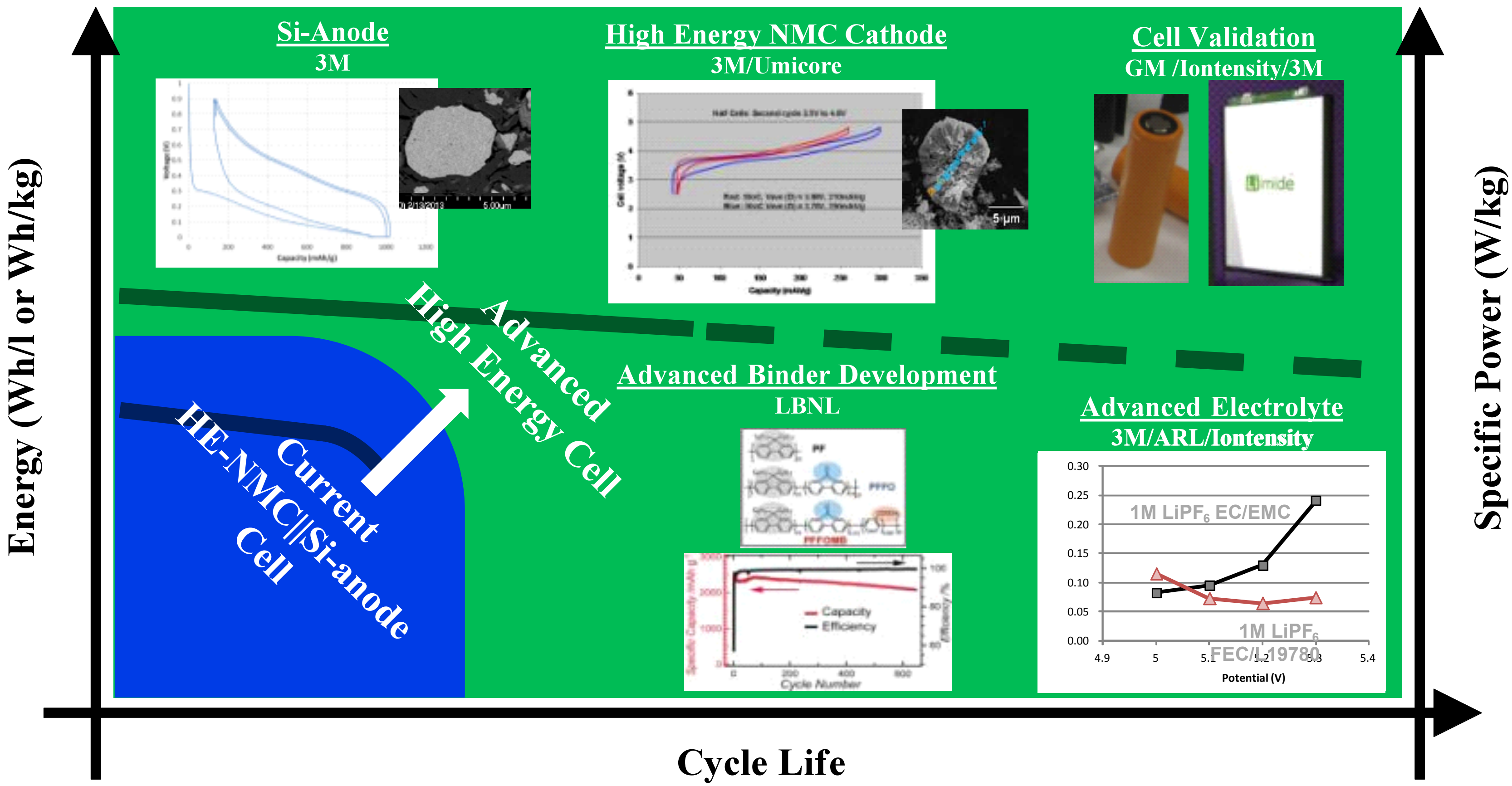


Milestones

Month / Year	Milestone	Status
Phase I (Oct 1st, 2013 to Sept 30th, 2014)		
Dec / 2013	Scale up baseline anode and cathode material	✓
April / 2014	Baseline cells shipment	✓
	Phase II (Oct 1st, 2014 to March 31st, 2016	
Aug / 2015	Advanced anode and cathode materials selection	✓
Dec / 2015	Advanced anode and cathode materials scale up	✓
March / 2016	Data package – Advanced cells	✓
April / 2016	Advanced cells shipment	✓

Approach

Synergistic Team Approach to Address Vital Components.



Approach

1 - Develop Advanced Material to meet Energy Targets

Si Alloy Anode
Scalable process to develop high capacity Si alloy with stable microstructure

Binder - Si Anode
Innovative conductive binder for superior Si anode composite

High Energy NMC Cathode
Develop composition with high Wh/kg to increase cell energy

Advanced Electrolyte / Additives
SEI and high voltage stability to enhance performance

2 - Characterize Performance in 18650 / Pouch Cells

Electrode Formulation Study

Tune Formation Protocol

Evaluate Dispersion, Roll to Roll Coating and Drying

Gap Analysis and Diagnostics

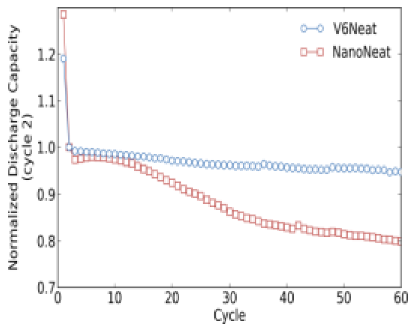
Energy and Life Validation

Silicon Alloy Anode Development - 3M

Developed advanced Si alloy anode with better properties

Baseline Material

3M Si Alloy Anode shows excellent cycling and coulombic efficiency compared to Si nano-particles

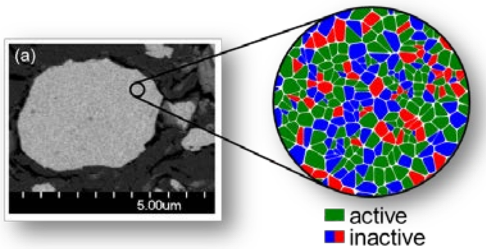


Journal of The Electrochemical Society, **161** (5) A783-A791 (2014)

Advanced Material

Develop Si alloy to target

- 20% ↑ mAh/g
- 10% ↑ mAh/cc
- Higher efficiency



Si Alloy	BET (m^2/g)	1st Lithiation (mAh/g)	1st Delithiation (mAh/g)	1st Delithiation (mAh/cc)	First Cycle Efficiency (%)	Manufacturability
Advanced Material	--	1170	1060	3370	90.4	✓
Baseline Material	3.5	1050	900	3280	85.7	✓

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Silicon Alloy Anode Development - 3M

Developed advanced Si alloy anode with better properties

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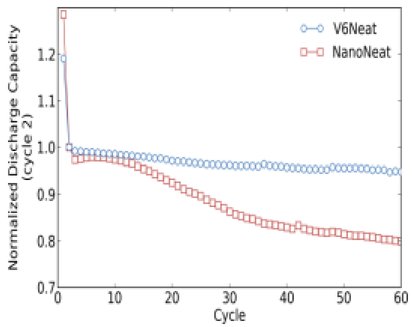

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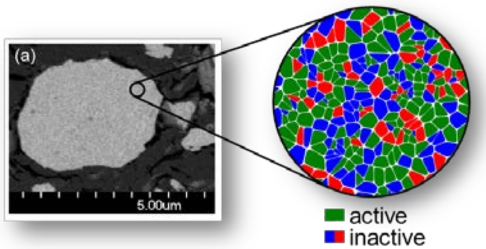

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Silicon Alloy Anode Scale Up - 3M

Demonstrated material scale up & commercial manufacturing feasibility

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Helping to build a better battery

Article by: SUSAN FEYDER , Star Tribune

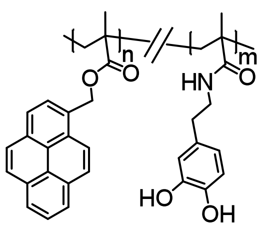
A 3M pilot project is making longer-lasting lithium ion batteries for consumer electronics. Next up: electric vehicle batteries.

High volume manufacturing feasibility underway.

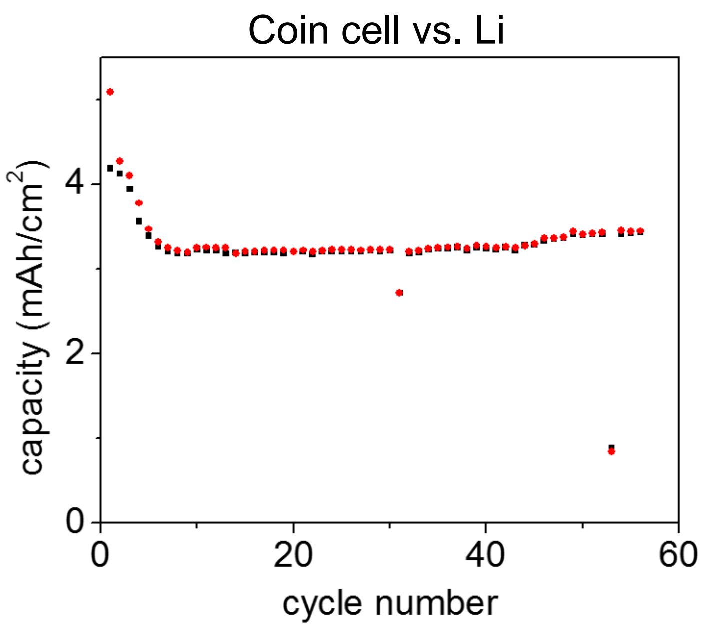
Scale-up plan to meet the demand forecast.

Binder Development - LBNL

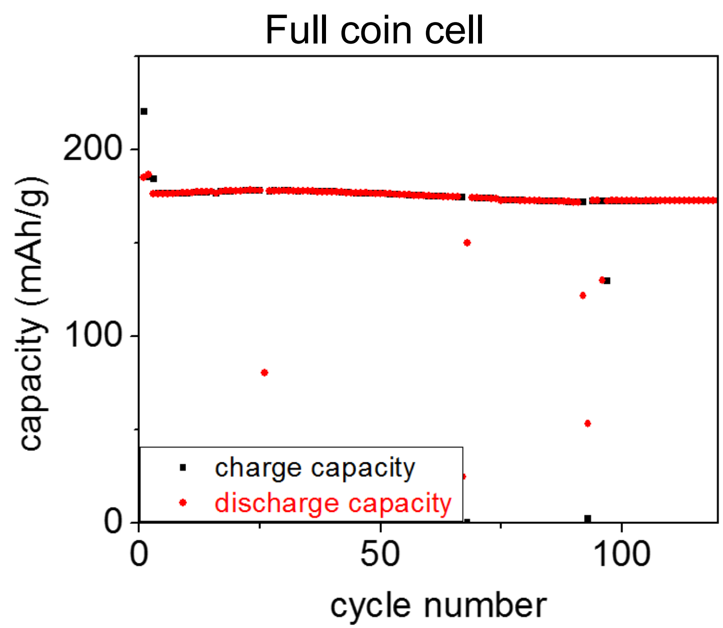
Demonstrated higher areal capacity electrodes with Si Alloy Anode



PPyDMA



PPyDMA with Advanced Si anode electrode
C/10, 0.005V-1V; constant voltage until 0.02C at the end of lithiation
1st cycle efficiency: 82.35%, 1st cycle delithiation capacity: 1175.9 mAh/g
50th cycle efficiency: 99.83%, 50th cycle delithiation capacity: 955.3 mAh/g



PPyDMA/ Advanced Si anode electrode w/o graphite; C/10 for 2 cycles, then C/3; 1st cycle efficiency: 82.34% (prelithiation with SLMP); Electrolyte: EC/DEC=3/7, 30% FEC, 1.2M LiPF6; Capacity reported based on cathode active materials

H.E. NMC Cathode Development - 3M

Developed advanced cathode material with better properties

Two Concepts: Core-Shell and Coated NMC

Core-Shell NMC

- Small advantage in energy compared to alternatives
- Challenges for cycle life, rate capability and gassing

3M coatings on NMC

- Better cycle life and energy
- Better rate capability

Cathode	BET (m^2/g)	1st Lithiation (mAh/g)	1st Delithiation (mAh/g)	First Cycle Efficiency (%)	Manufacturability
Advanced Material	0.31	230	211	91.9	✓
Baseline Material		273	227	83.3	✓

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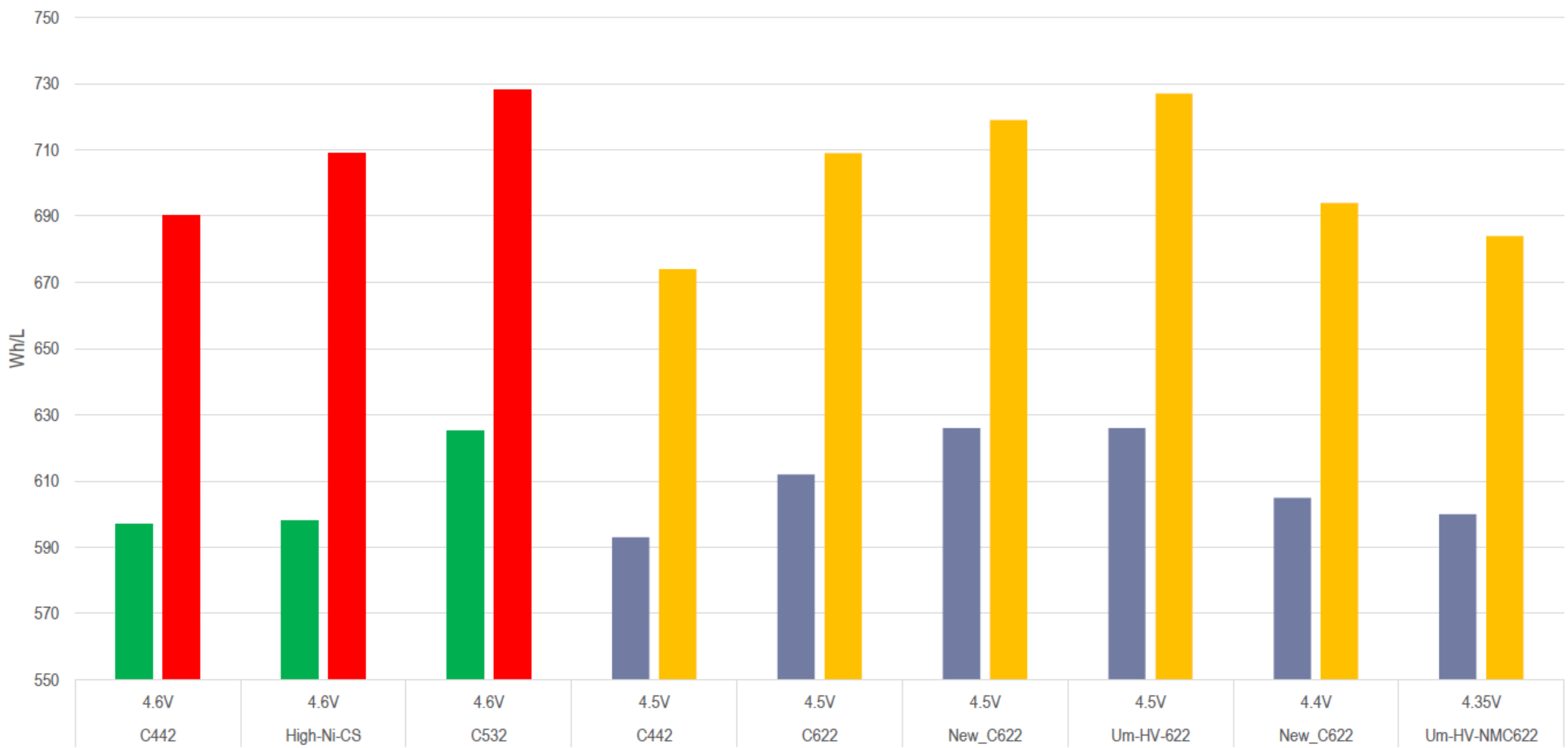
Developed different candidates and demonstrated energy improvement



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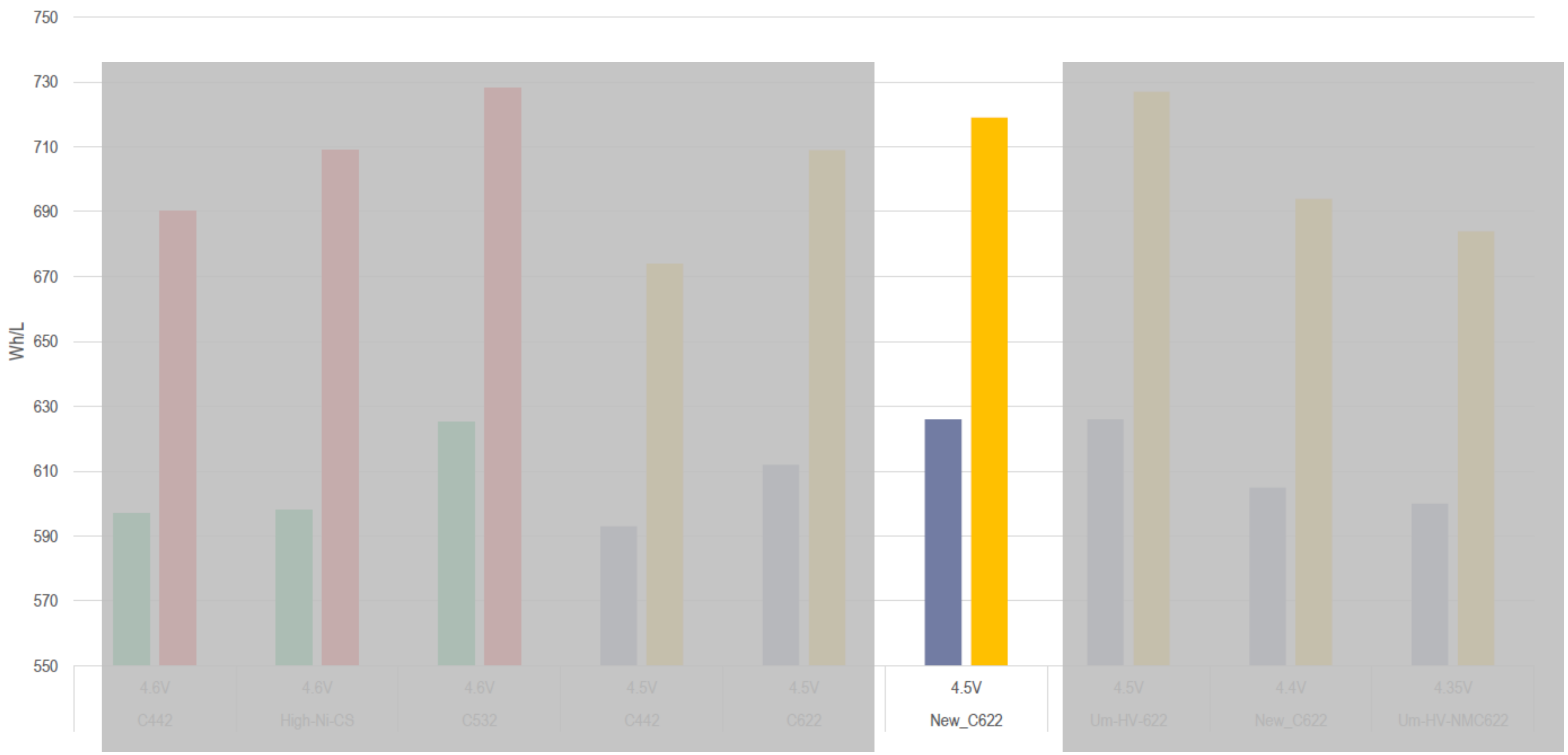


H.E. NMC Cathode Scale Up - Umicore

Demonstrated material scale up & commercial manufacturing feasibility

Process chart

H_3PO_4 solution + $La(NO_3)_3$ solution

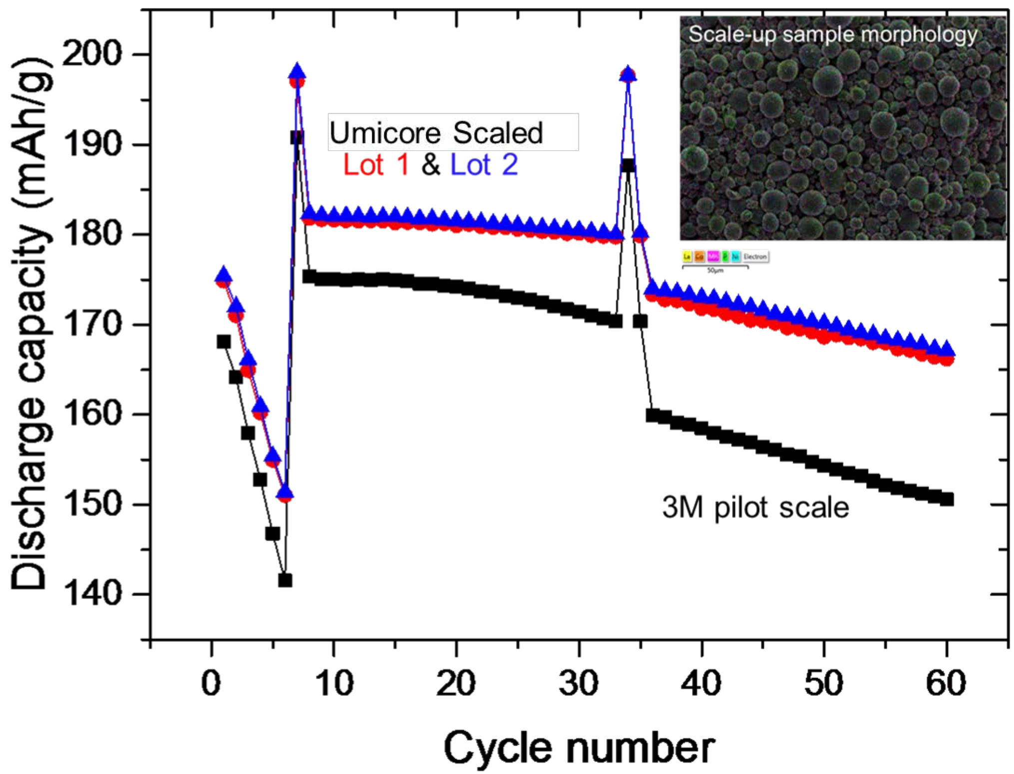
- ✓ Precipitation
- ✓ change to white suspension

$LaPO_4$ Solution + HX12-G3

Mixing

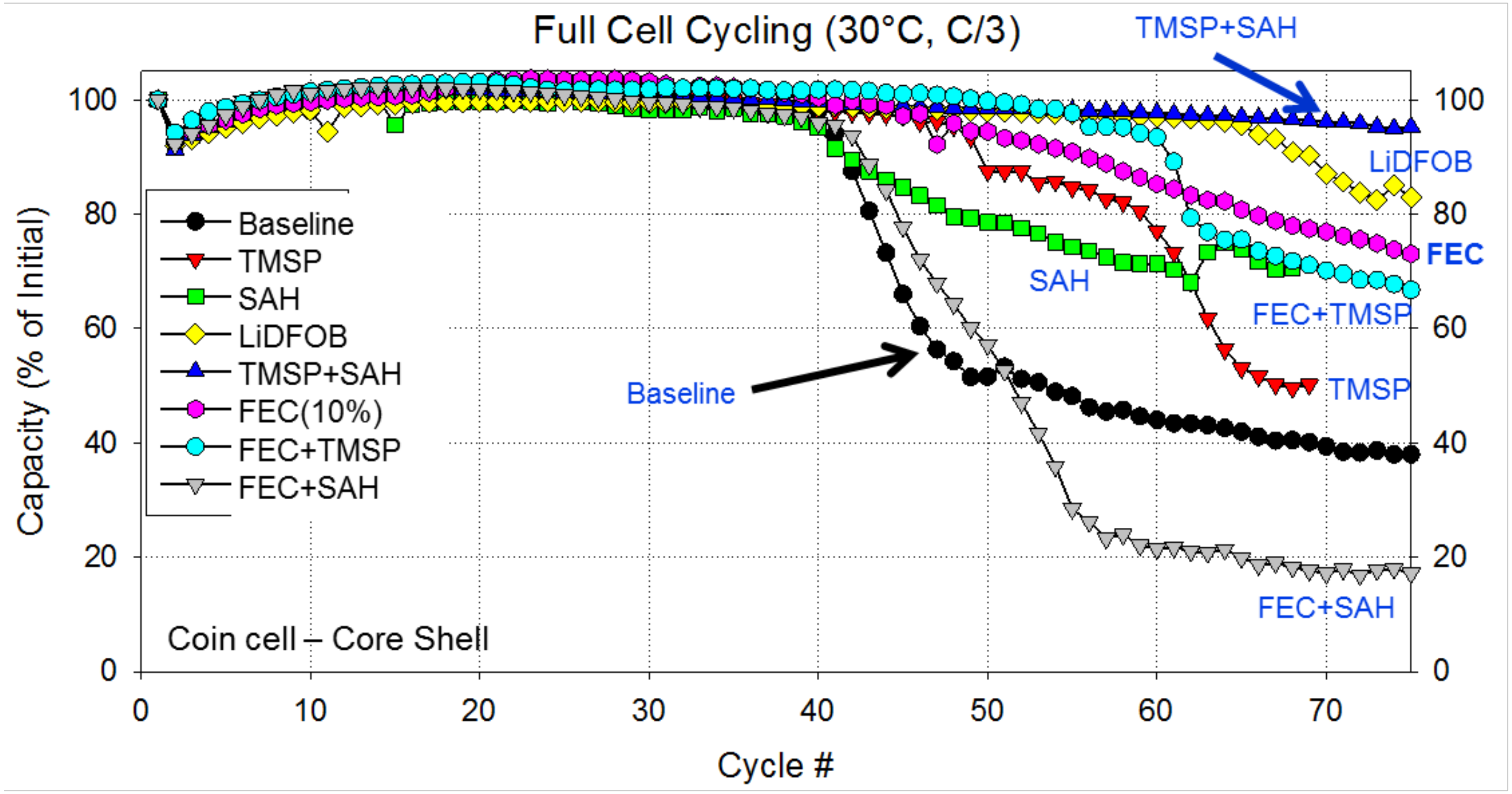
Dry in vacuum 120°C/overnight

Firing



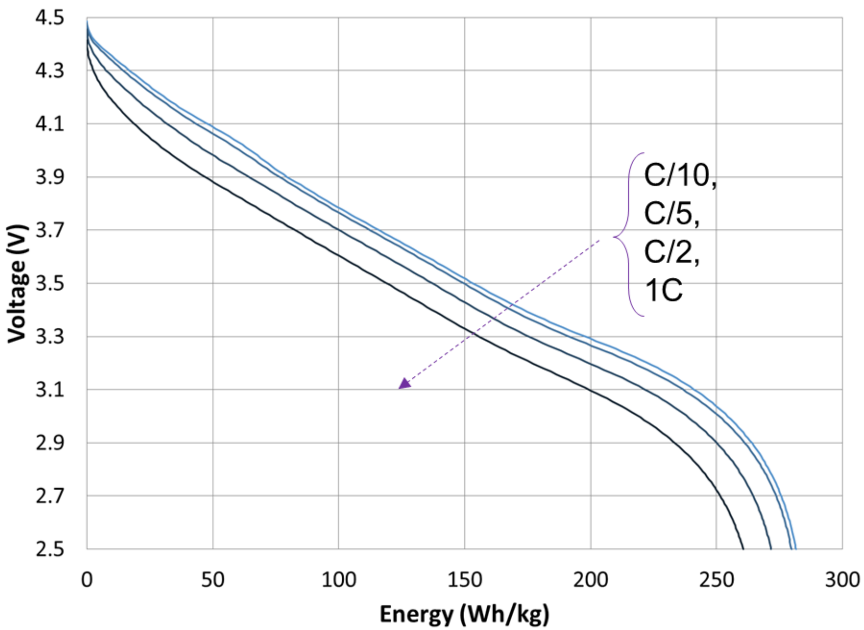
Electrolyte Development - ARL

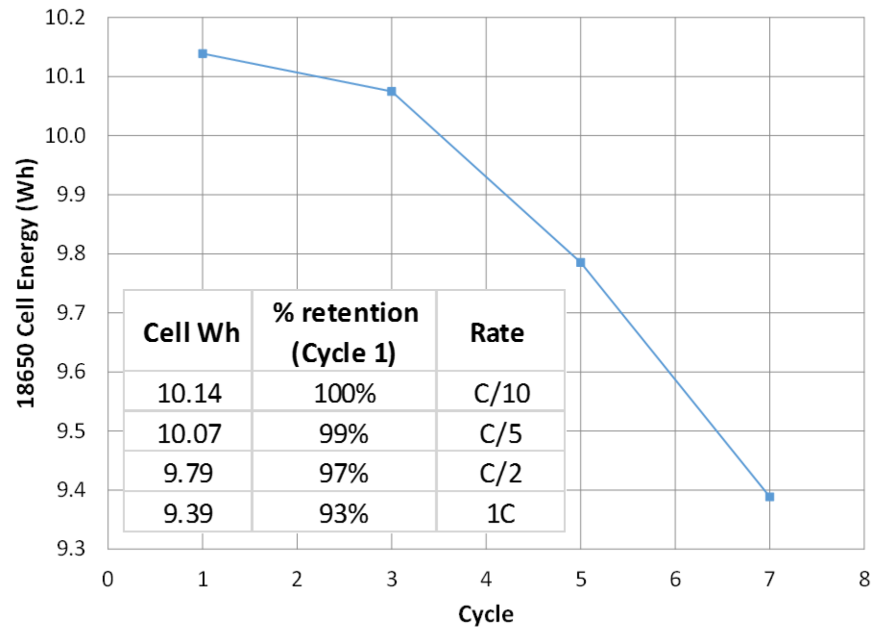
Identified cycle life enabling electrolyte for advanced chemistry



Advanced Chemistry 18650 Evaluation - 3M

≥ 93% energy retention at 1C rate





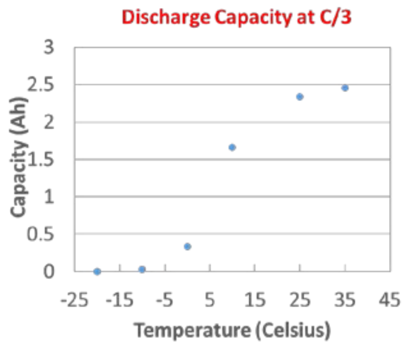
Cell Wh	% retention (Cycle 1)	Rate
10.14	100%	C/10
10.07	99%	C/5
9.79	97%	C/2
9.39	93%	1C

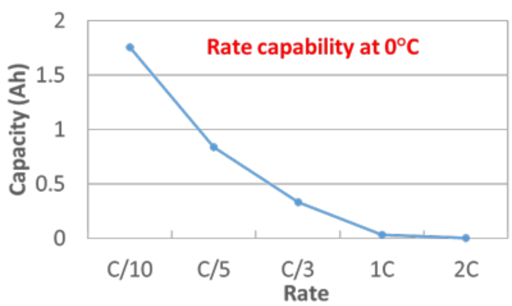
~24% increase in energy by *further* cell design optimization (12um separator, 58 mm wide cathode, N/P=1.05, Tighter winding)
Si alloy anode from 3M production scale facility; High energy NMC cathode from 3M pilot scale facility

Advanced Chemistry 18650 Evaluation - GM

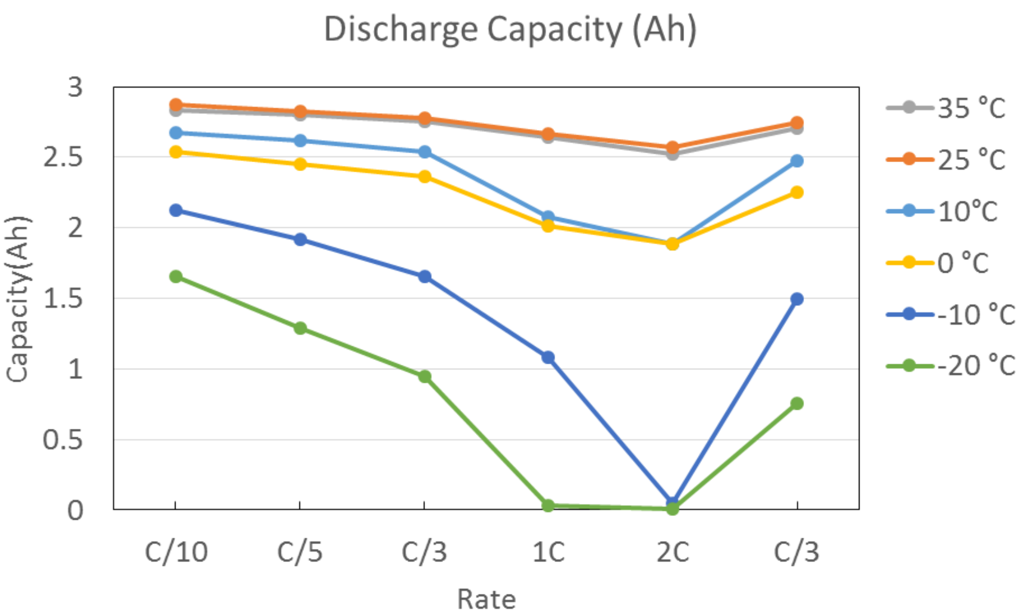
Improved rate capability at low temperatures

Baseline Material





Advanced Material

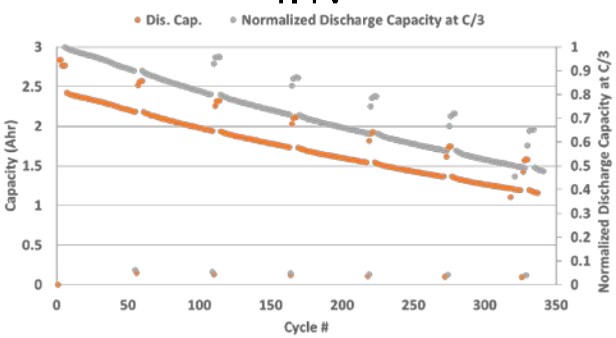


Low capacity at high C-rate at low temperature may be due to resistance built up during previous test.
Si alloy anode from 3M production scale facility
High energy NMC cathode from 3M pilot scale facility

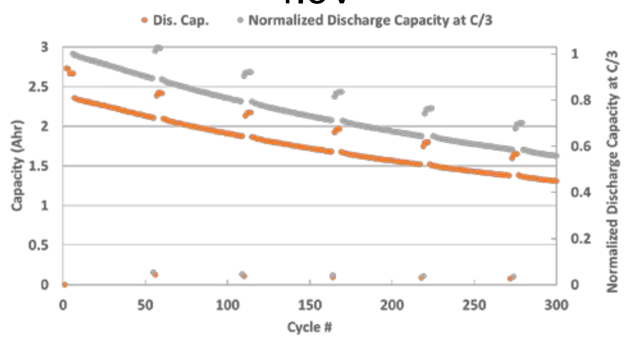
Advanced Chemistry 18650 Evaluation - GM

Effect of UCV on Cycle Life

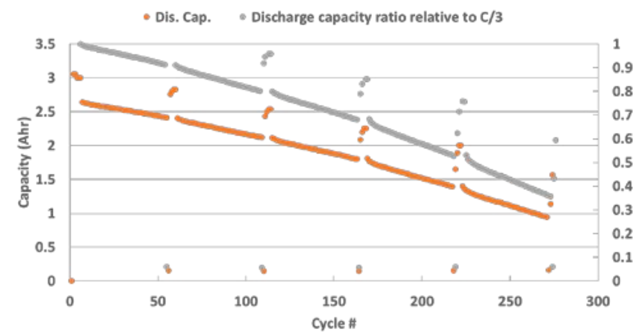
4.4V



4.5V



4.6V



C/3 cycling 5%-95% SOC; After every 50 cycles at C/3, HPPC and C/10 capacity check were carried out

Si alloy anode from 3M production scale facility

High energy NMC cathode from 3M pilot scale facility

Advanced Chemistry 18650 Evaluation - GM

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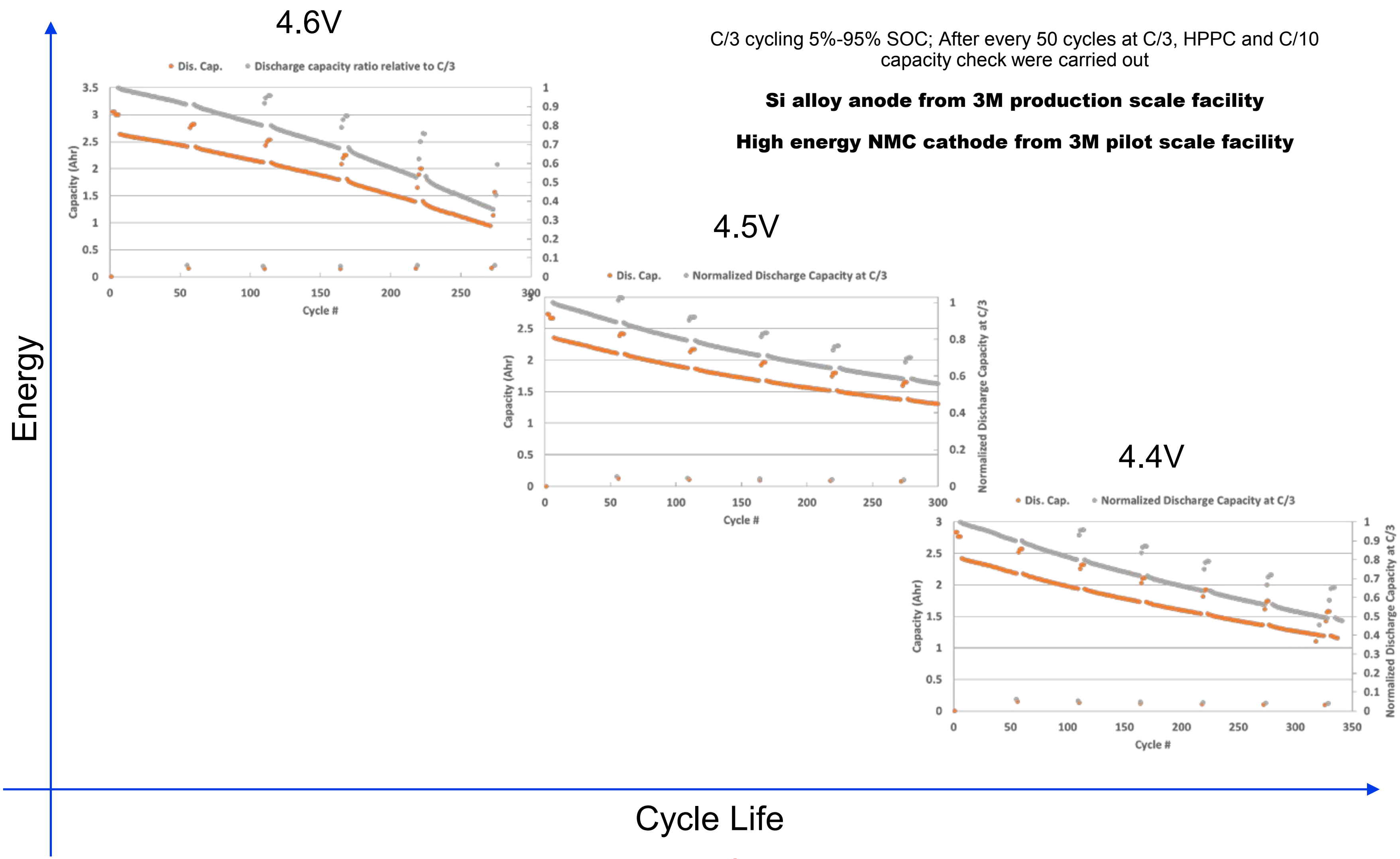

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Gap Analysis, Advanced vs. Baseline - GM

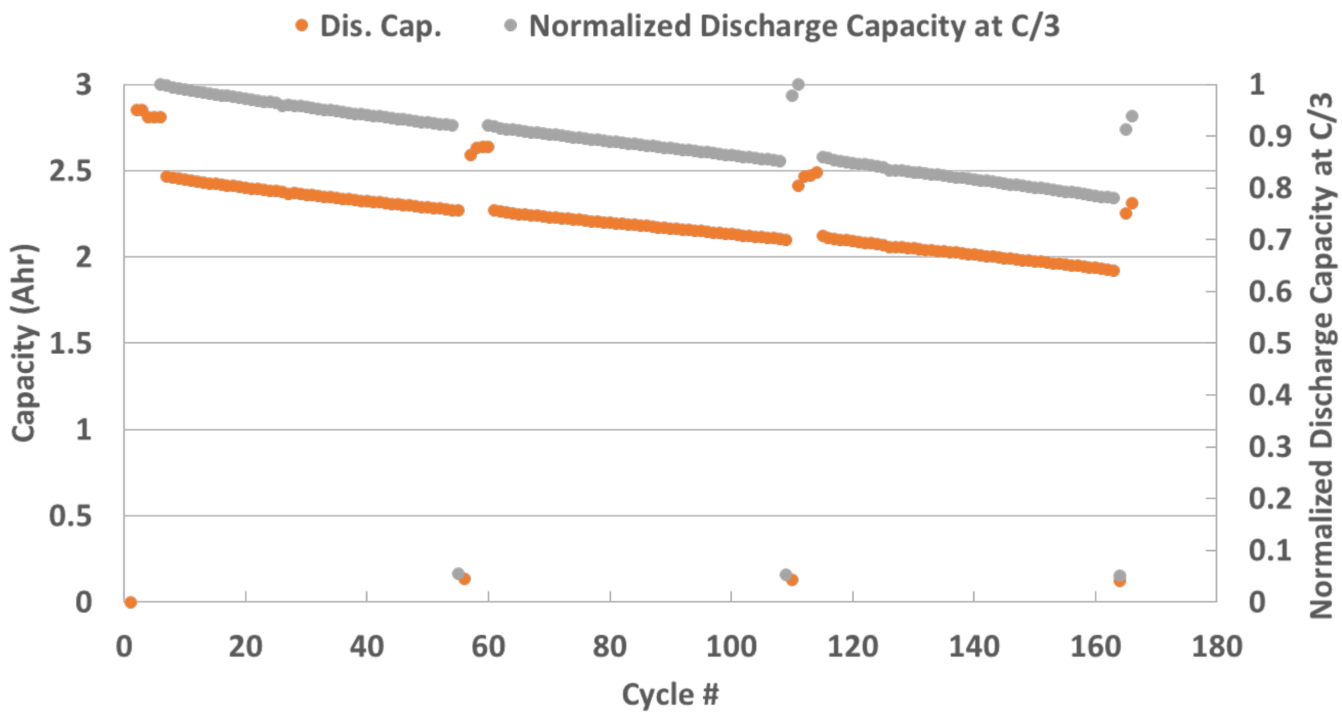
Improved key cell level properties. Cycle life improvement WIP.

	Unit	Target[1]	Benchmarks[2]		4.4-2.5 V		4.5-2.5 V		4.6-2.5 V	
			Cell Level	Wet Laminate Level[3]	Cell Level	Wet Laminate Level[3]	Cell Level	Wet Laminate Level[3]	Cell Level	Wet Laminate Level[3]
Gravimetric Energy Density	Wh/kg	400	192[4]	247[4]	206	260	218	274	234	295
Volumetric Energy Density	Wh/L	600	490[4]	490[4]	556	556	596	596	633	633
Gravimetric Discharge Power Density	W/Kg	800	366[5]	471[5]	676	853	691	870		
Volumetric Discharge Power Density	W/L	1200	933[5]	933[5]	1818	1818	1873	1873		
Gravimetric Regen Power Density	W/Kg	400	690[5]	888[5]	1396	1761	1528	1926		
Volumetric Regen Power Density	W/L	600	1757[5]	1757[5]	3756	3756	4146	4146		
Cycle life	cycles[6]	1000	45	45	194	194	189	189	158	158
Opt. Temp. Range	°C	-30~65	0~TBD	0~TBD	-20~35	-20~35	-20~35	-20~35	30	30

[1] - End of life requirement from F; [2] - Beginning of life data; [3] - Including electrode, separator, and electrolyte; [4] - Data from C/3; [5] - 40% SOC; Vm, 25°C; [6] - 35% capacity loss at C/3 with 90% DOD range

Advanced Chemistry 18650 Evaluation - GM

Cycle life testing with deliverable cells in progress



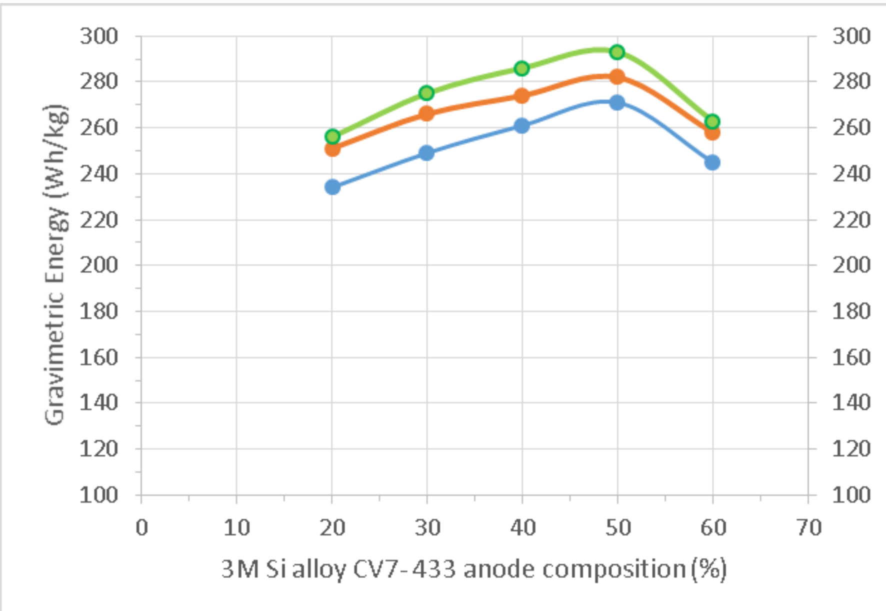
Si alloy anode from 3M production scale facility

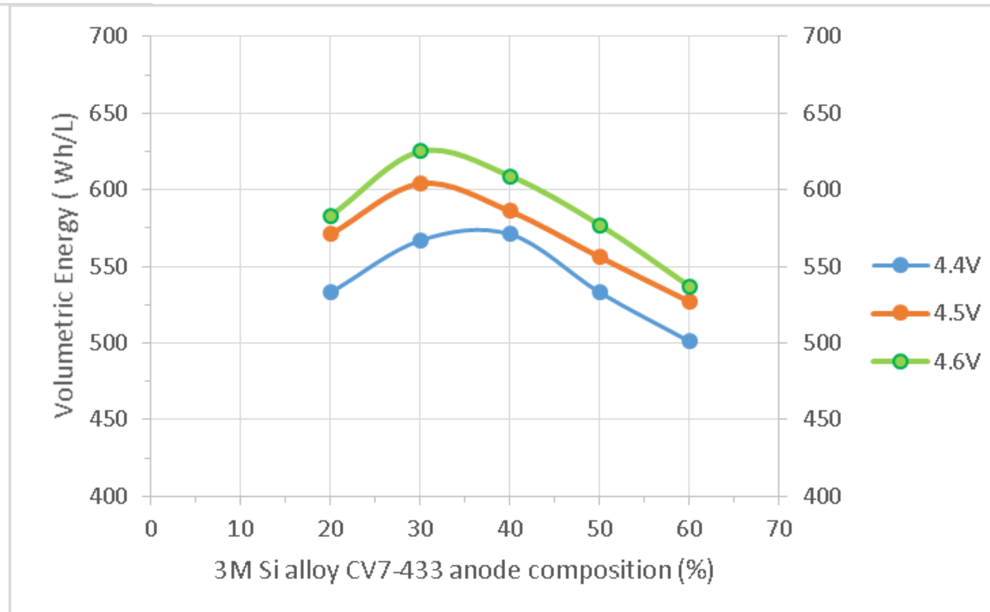
High energy NMC cathode from Umicore production scale facility

C/3 cycling 5%-95% SOC; 80% capacity retention: 135 cycles; RPT's (C/3, HPPC and C/10 capacity) after every 50 cycles

Pouch Cell Evaluation - Iontensity

Identified pouch cell energy levels with varying wt% content of Si alloy anode





Si alloy anode from 3M production scale facility
High energy NMC cathode from 3M pilot scale facility
Cycle life testing initiated

Cell Sampling to Argonne National Lab - 3M

Sampled 18650 cells with advanced chemistry

Rate	**C/15**	**C/15**	**Irreversible % (After 1st cycle)**	**C/10**	**C/10**	**Irreversible % (after 3 cycles)**	**C/5**	**C/5**	**C/2**	**C/2**	**1C**	**1C**
Cycle #	**0**	**0**		**1**	**2**		**3**	**4**	**5**	**6**	**7**	**8**
Avg	3390	2782	17.9%	2865	2881	15.0%	2864	2864	2823	2818	2759	2751
St Dev	52	57	0.5%	56	54	0.5%	53	53	53	52	56	56
Relative St Dev	1.5%	2.0%	3.0%	2.0%	1.9%	3.0%	1.9%	1.8%	1.9%	1.9%	2.0%	2.0%

Response to Previous Year Reviewers' Comments

- Si Alloy anode and advanced cathode: Cycle life improvements for commercialization
  - Made improvements but achieving long cycle life (>1000 cycles) is still a challenge.
  - Working on key enablers: High voltage electrolyte, anode composite, stable electrochemical couple match

- Si Alloy anode and advanced cathode: Powder production
  - Generated >1000 kg Si alloy anode materials (advanced material).
  - Generated >50 kg of particle coated NMC cathode material.

- Harmonizing test conditions and cycling test
  - Each partner used the same material lot or coated electrode
  - Balanced approach:
    - Cycle life testing in large cells were harmonized for C/3 rate
    - Optional testing via partner's preferred conditions

Collaboration and Coordination

- 3M
  - Sample Electrodes (ARL, Iontensity, GM), Si Alloy Anode Powder (Iontensity, GM, LBNL), High Energy NMC Cathode Powder (Iontensity, GM) and Cells (GM).
- ARL
  - Develop and Sample Electrolyte and Additives (3M, Iontensity).
- GM
  - Evaluate, Analyze and Diagnose Cells (3M,Iontensity).
- LBNL
  - Optimize and Evaluate Binder Chemistry for Si Alloy Anode (3M).
- Iontensity
  - Optimize Composite Electrodes and Pouch Cells. Sample Cells (GM, 3M).
- Umicore
  - Optimize Process and Scale Up Cathode Material. Sample Materials (3M).

Remaining Challenges / Barriers

- Long cycle life
  - Electrolyte formulation for high voltage (4.5V) chemistries
  - Superior Si anode composite
    - Binder evaluation in large format cells such as 18650 or pouch cells
    - More stable SEI formation
    - Further reduced controlled volumetric expansion over life
  - Stable match of high voltage cathode and high voltage electrolyte

Proposed Future Work

- Complete life testing with advanced chemistry
- Analyze life degradation root causes
- Discuss advanced chemistry performance from cells sampled to ANL
- Prepare final project report

Summary

- Successfully leveraged collaborative R&D
  - Anode and Cathode material development at 3M
  - Binder development on 3M Si Alloy Anode at LBNL
  - Cathode material scale up and process optimization at Umicore.
  - Gap analysis, cell evaluation and validation at GM
  - Electrolyte and additive screening for baseline and advanced chemistry at ARL
  - Advanced chemistry's pouch format cell feasibility at Iontensity.

- Successful Scaled up Baseline and Advanced Materials

- Demonstrated performance improvement

Q & A